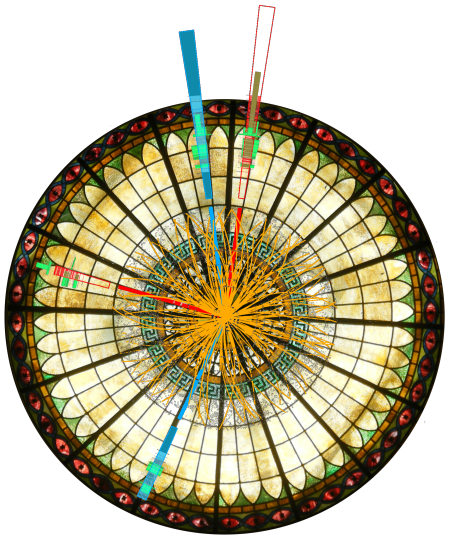
DIS2015

NLO+NLL limits on W', Z' gauge bosons masses in general extensions of the SM



JHEP 1412 (2014) 092

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April 29, 2015

Introduction

- New heavy resonances, W′, Z′ predicted in a variety of models
  - GUT
  - Extra dimensions

Collider Limits

- **SSM**, String inspired Z′, **LR**
- Most stringent limits obtained in leptonic final states:
  - ~ 25 searches (both ATLAS and CMS)
    $\Rightarrow$ in **SSM** $M_{Z'} > 2.9$, $M_{W'} > 3.3$ TeV
- Most of them obtained using **PYTHIA** LO+PS rescaled to NNLO with **FEWZ** or **ZWPROD**
  - No interferences with SM W and Z bosons

Introduction

- New heavy resonances, W′, Z′ predicted in a variety of models
  - GUT
  - Extra dimensions

Our approach:

- Public code **RESUMMINO** already implements soft-gluon resummation for:
  - Z′, gaugino and slepton pair production
  - Added the W′ $\to \ell\nu$ process
- Present QCD resummation predictions for $pp \to W/W' \to \ell\nu$ and $pp \to Z/Z' \to \ell\ell$
  - Include the interferences
  - Allow general couplings

- Compare our results with our version of PYTHIA which includes interferences and FEWZ.

I) Introduction

II) Theoretical setup

III) Numerical Results

IV) Gauge boson mass limits in general SM extension

V) Conclusion

PYTHIA (6.4.27) **LO+PS**:

- Implemented the full $qq^{(\prime)} \to Z'/W' \to \ell\ell, (\ell\nu)$
- Includes interferences with W, Z bosons
- Automatic calculation of the total width
- SM like couplings:
  - $\bar{\nu}_\ell \ell W'^{+}, \bar{\ell}\nu_\ell W'^{-} \sim \frac{g}{2\sqrt{2}}\gamma^\mu(V_\ell - A_\ell\gamma_5)$,
  - $\bar{q}q'W'^{\pm} \sim \frac{g}{2\sqrt{2}}U_{\mathrm{CKM}}\gamma^\mu(V_q - A_q\gamma_5)$.

FEWZ **LO, NLO, NNLO**:

- Fixed-order, fully exclusive $\to$ arbitrary cuts
- Extrapolate SM predictions:
  - Fed with the W', Z' bosons properties from PYTHIA
  - Observables need to be rescaled by the proper combination of couplings (not always possible)
- No interferences

RESUMMINO **NLO+NLL**:

- Our implementation of the W/W' and Z/Z' into leptons process
- Resummation of the small p_T and production threshold regions
- Resums the large logarithms in these regions
  - $p_T \to 0,\ z \equiv Q^2/s \to 1$
- Matched to fixed-order NLO calculation
  - $\sigma_{ab} = \sigma_{ab}^{(\mathrm{res.})} + \sigma_{ab}^{(\mathrm{f.o.})} - \sigma_{ab}^{(\mathrm{exp.})}$.
- The code also allows for fixed-order LO, NLO

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Comparison

- Comparison of **RESUMMINO**, **PYTHIA** and **FEWZ** for various models @ **LHC14**
- Sequential Standard Model (SSM), and different realizations of $\mathcal{G}_{221}$ models:
  - $\mathcal{G}_{221} \equiv \mathrm{SU}(2)_1 \times \mathrm{SU}(2)_2 \times \mathrm{U}(1)_X$
  - *Un-unified* (UU), *Non-Universal* (NU)
- In total **5** benchmark points with $M_{W'} = 4$ TeV:
  - B1 (SSM), $\Gamma_{W'} = 143$ GeV
  - B2 (UU), $\Gamma_{W'} = 237$ GeV
  - B3 (UU), $\Gamma_{W'} = 125$ GeV
  - B4 (NU), $\Gamma_{W'} = 217$ GeV
  - B5 (NU), $\Gamma_{W'} = 141$ GeV
- MSTW 2008 global fit at LO, NLO, NNLO and corresponding error sets at 68% C.L.

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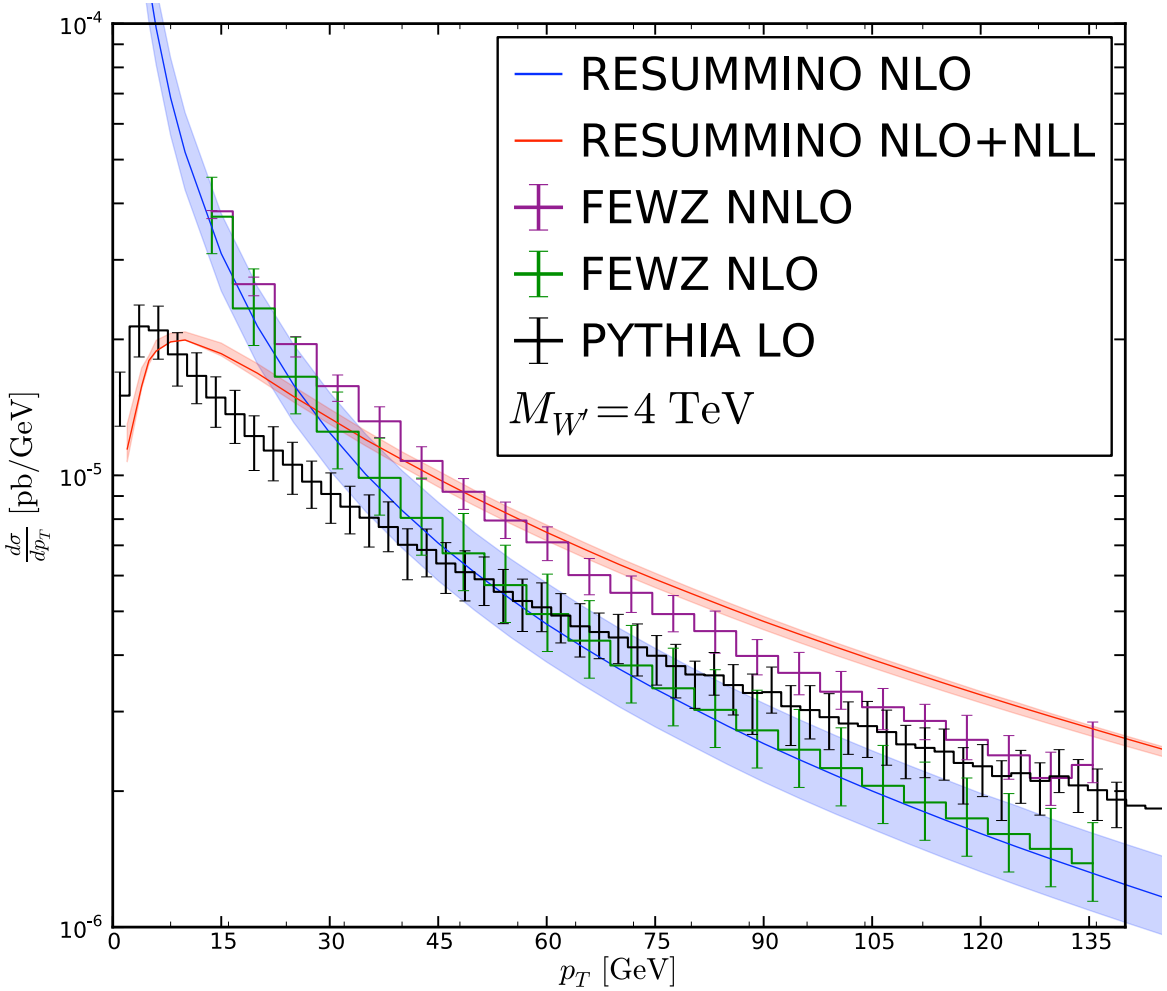
p_T spectrum

- SSM, W'^+ of 4 TeV with $Q_{e^+\nu} > 3/4 M_{W'}$ to limit interferences and W contribution



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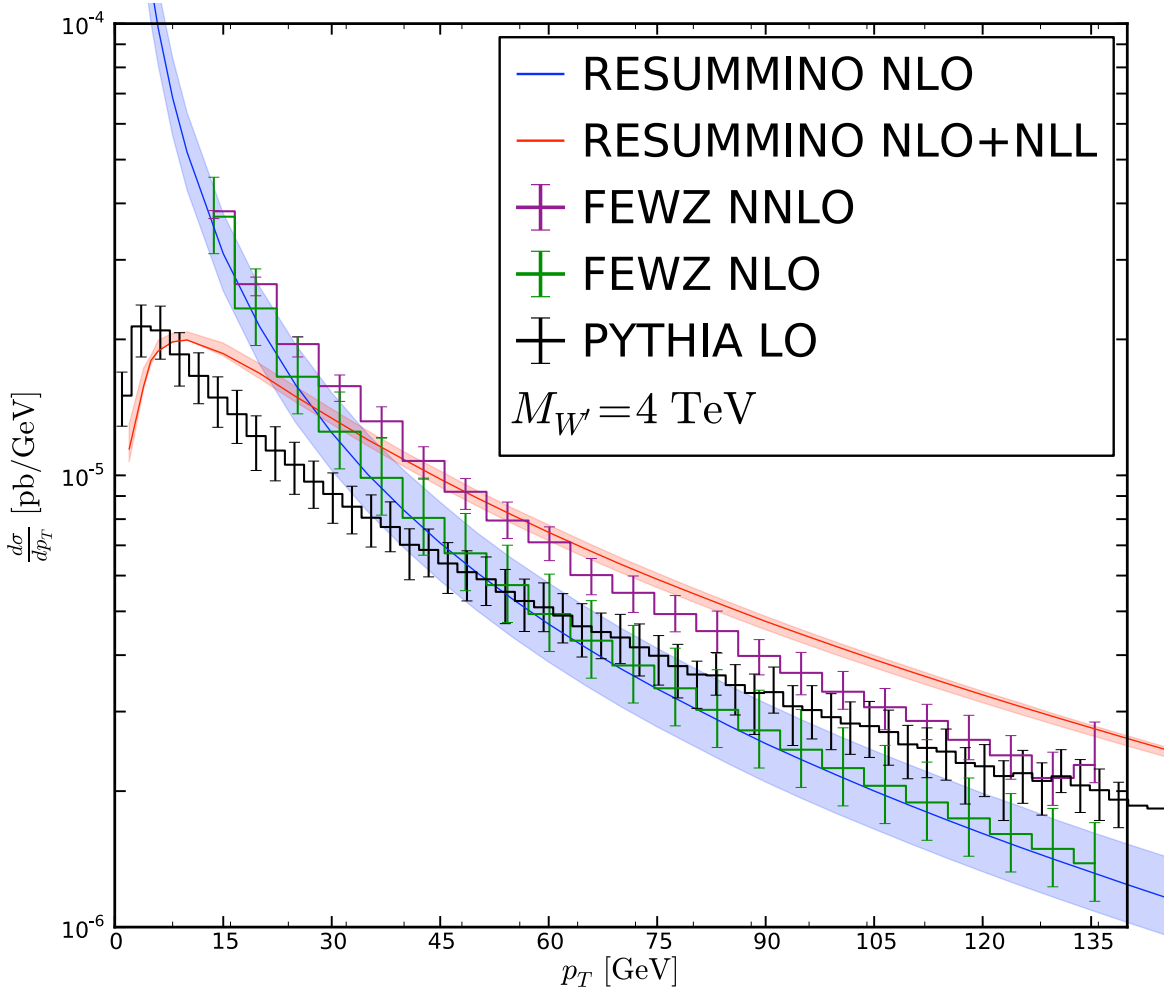
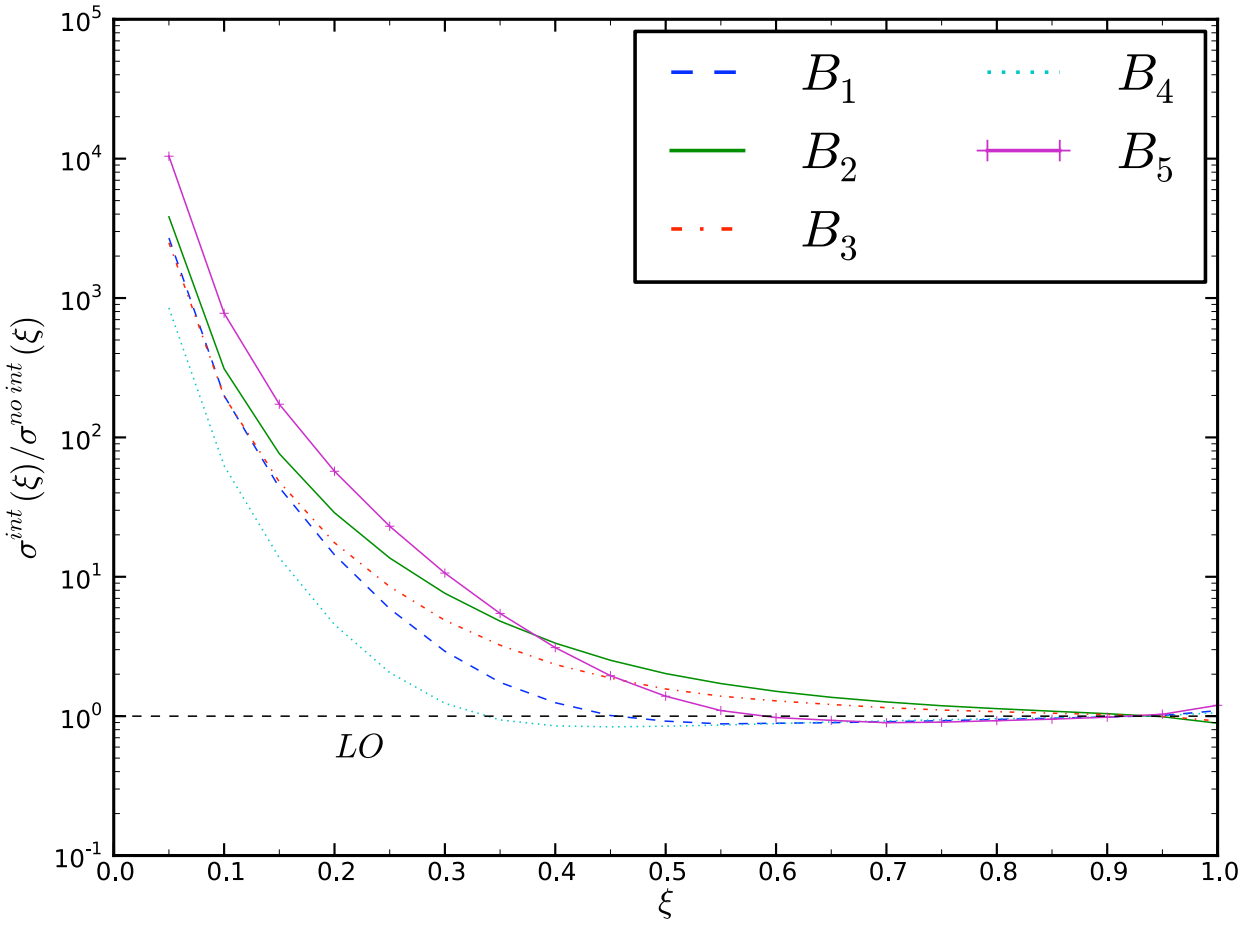


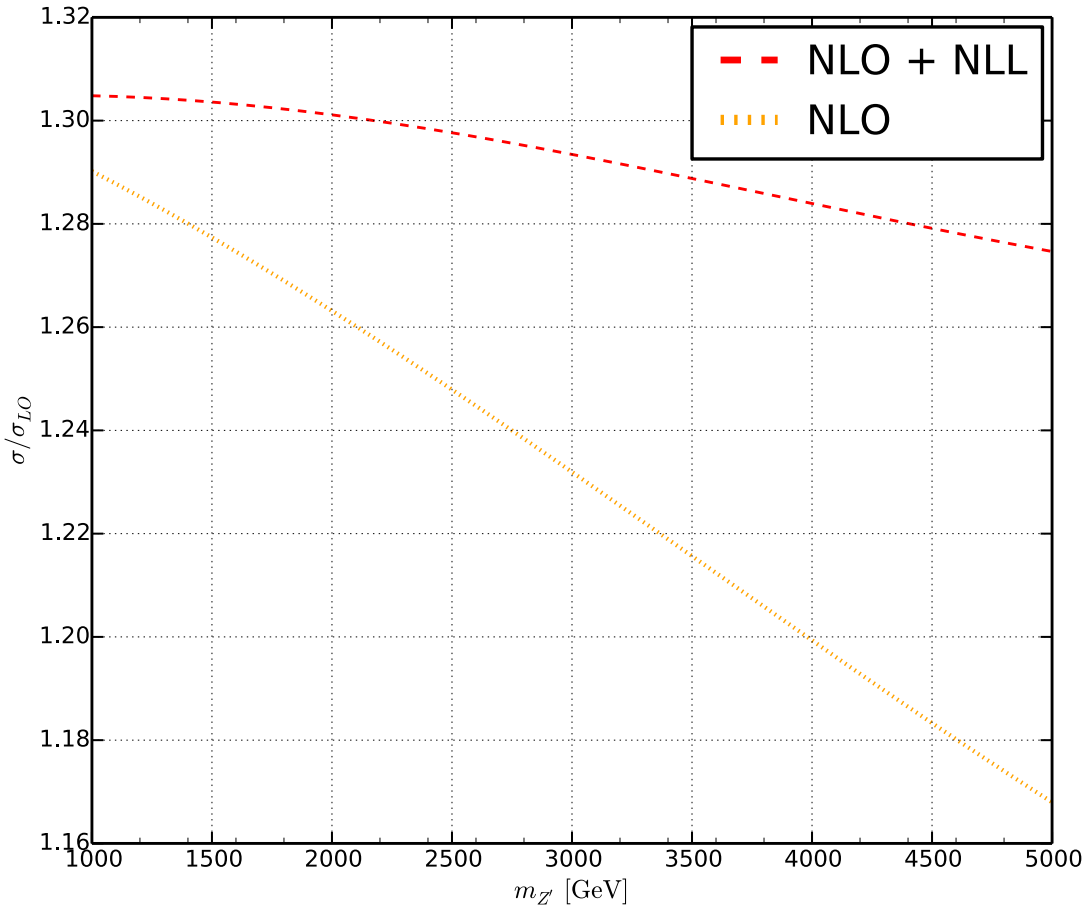
- Total cross sections for the 5 benchmark points:
  - at LO PYTHIA, FEWZ, RESUMMINO $\sim 1 - 2\%$
  - at NLO RESUMMINO, FEWZ $\sim 1 - 2\%$

Importance of the interferences

- σ: $Q_{e^+\nu} > 3/4 M_{W'} \Rightarrow$ Interferences still important
  - $Q_{e^+\nu} > \xi M_{W'}$



Importance of the Resummation



- As the mass increases we probe more and more the threshold region

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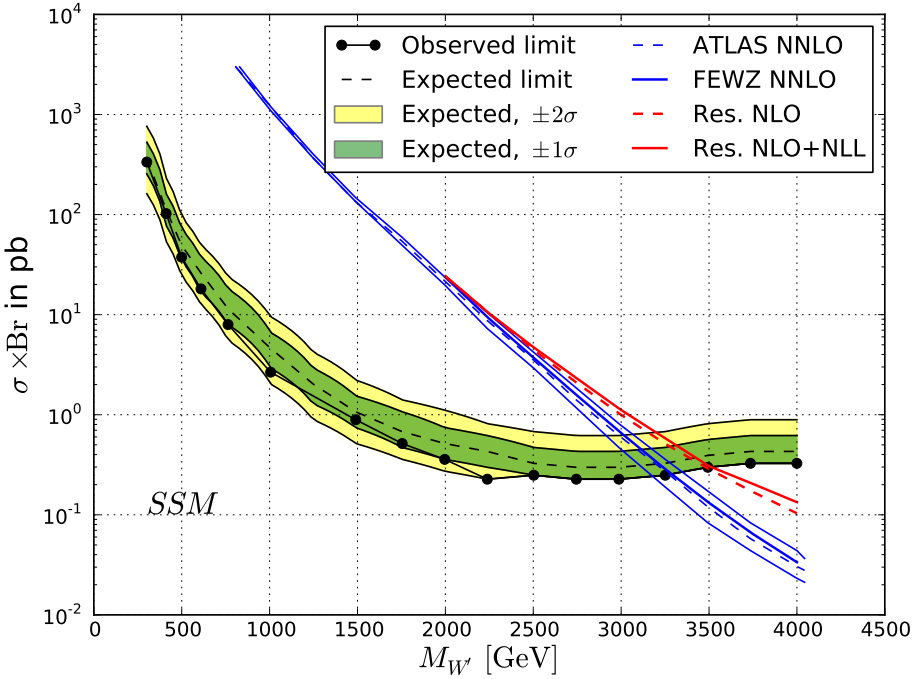
ATLAS W′- SSM

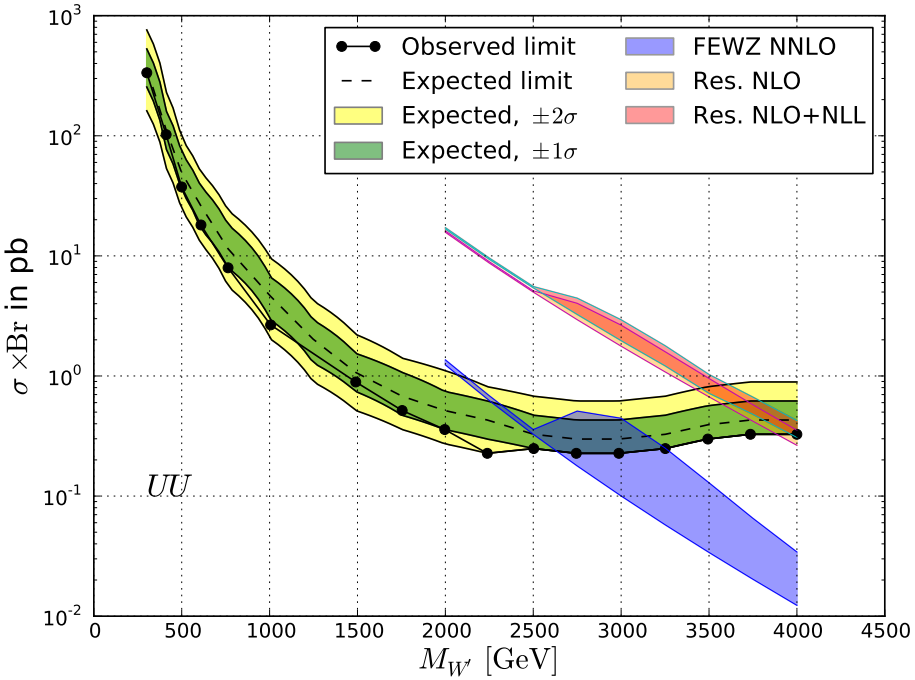
- Re-analysis of the ATLAS results at $\sqrt{s} = 8$ TeV, 20.3 fb^{-1}
  - PYTHIA LO+PS, $W^+ + W^-$ with $Q > 0.4 M_{W'}$
  - Rescaled to NNLO with ZWPROD $\Rightarrow$ no interferences
  - $M_{W'}^{\mathrm{SSM}} > 3.24$ TeV



- $M_{W'}^{\mathrm{RES.}} > 3.5$ TeV

ATLAS W′ and Z′- UU

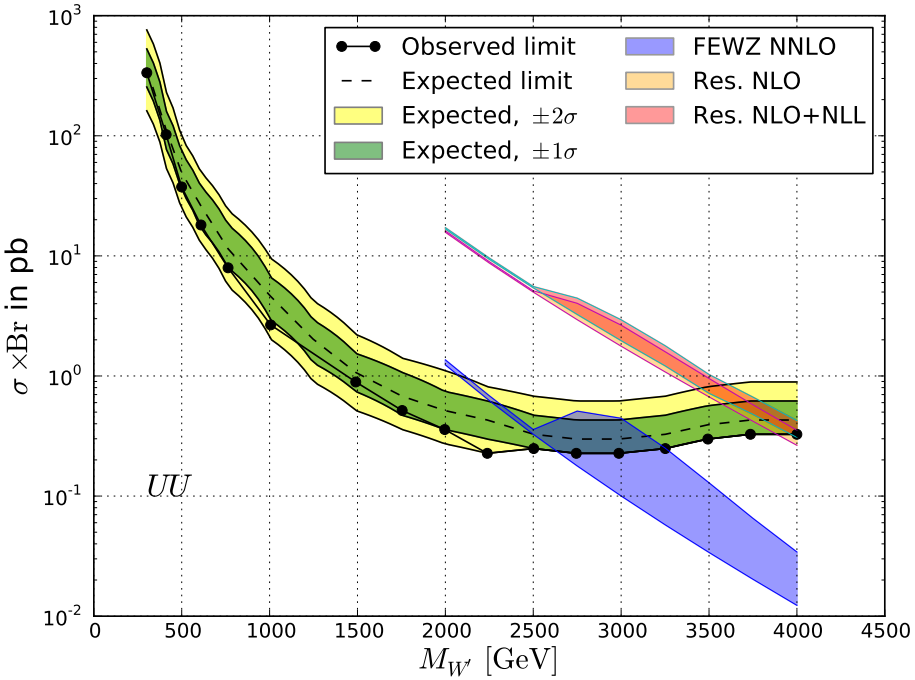
- Re-analysis of the ATLAS results at $\sqrt{s} = 8$ TeV, 20.3 fb^{-1}



- $\text{Res. NLO} + \text{NLL}/\text{Res. NLO} \simeq 20\%$
- Large interferences

ATLAS W′ and Z′- UU

- Re-analysis of the ATLAS results at $\sqrt{s} = 8$ TeV, 20.3 fb^{-1}

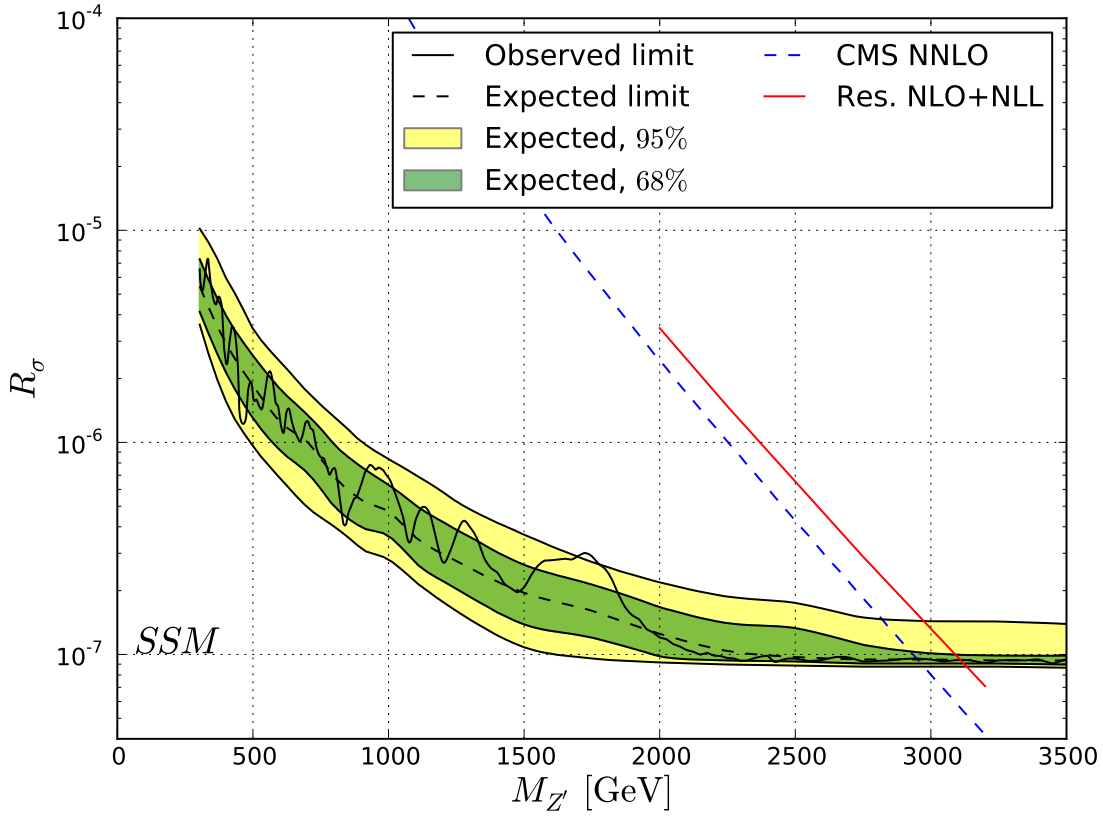


- $\text{Res. NLO} + \text{NLL}/\text{Res. NLO} \simeq 20\%$
- Large interferences

- $M^{\text{RES.}}_{W'/Z'} > 3.9 - 4$ TeV, improves from previous limits obtained from low-energy and precision observables.
- Holds for Z′ in UU: $M_{Z'} \simeq M_{W'} + \mathcal{O}(v^2/u^2)$

CMS Z′- SSM

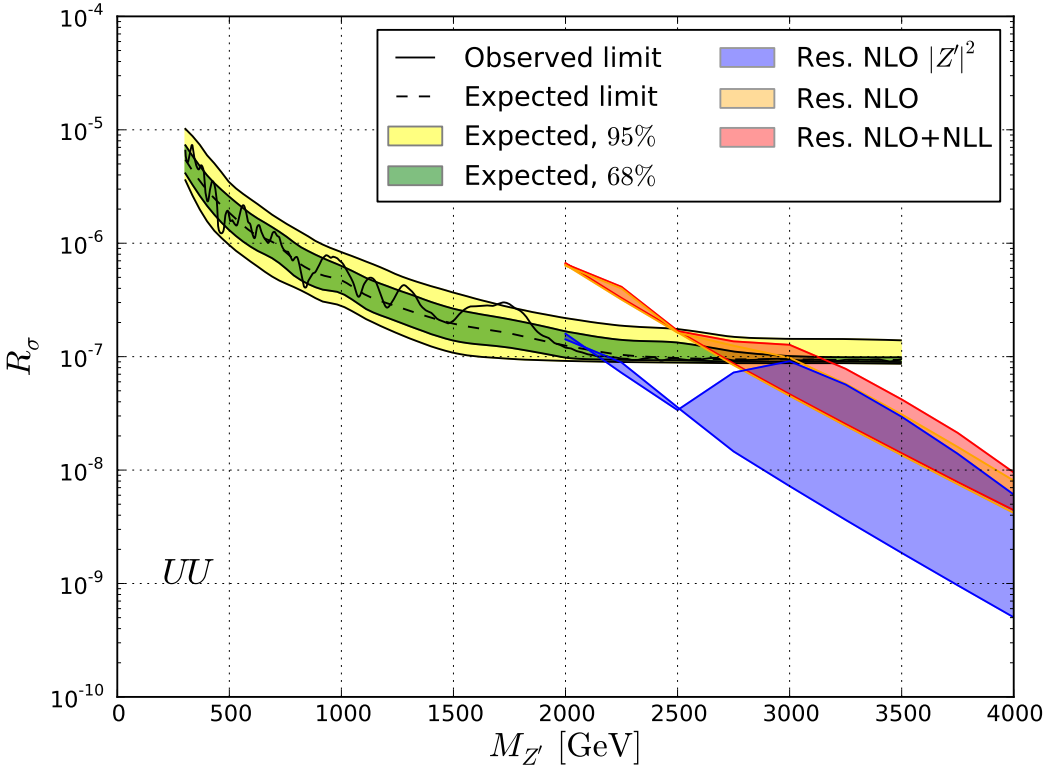
- Re-analysis of the CMS results at $\sqrt{s} = 8$ TeV, 20.6 fb^{-1}
- PYTHIA LO+PS rescaled @NNLO with ZWPROD
- $0.6 M_{Z'} < Q < 1.4 M_{Z'} \Rightarrow M_{Z'} > 2.96$ TeV



- Large interferences
- $M_{Z'}^{\mathrm{RES.}} > 3.2$ TeV.

CMS Z′- UU

- Re-analysis of the CMS results at $\sqrt{s} = 8$ TeV, 20.6 fb^{-1}
- $0.6 M_{Z'} < Q < 1.4 M_{Z'}$



- $M_{Z'/W'}^{\text{RES.}} > 2.75 - 3.2$ TeV, previous limits: 2.5 TeV.

Summary

Limits obtained from the Re-analysis

- **SSM**:
  - From ATLAS W′ analysis: $M_{W'} > 3.5$ TeV (3.24)
  - From CMS Z′ analysis: $M_{Z'} > 3.2$ TeV (2.96)
- **UU**:
  - From ATLAS W′ analysis: $M_{W'/Z'} > 3.9 - 4$ TeV
  - From CMS Z′ analysis: $M_{Z'/W'} > 2.75 - 3.2$ TeV
- also **NU**:
  - From ATLAS W′ analysis: $M_{W'/Z'} > 3.5$ TeV (3.6)
  - From CMS Z′ analysis: $M_{Z'/W'} > 3.25$ TeV (3.6)

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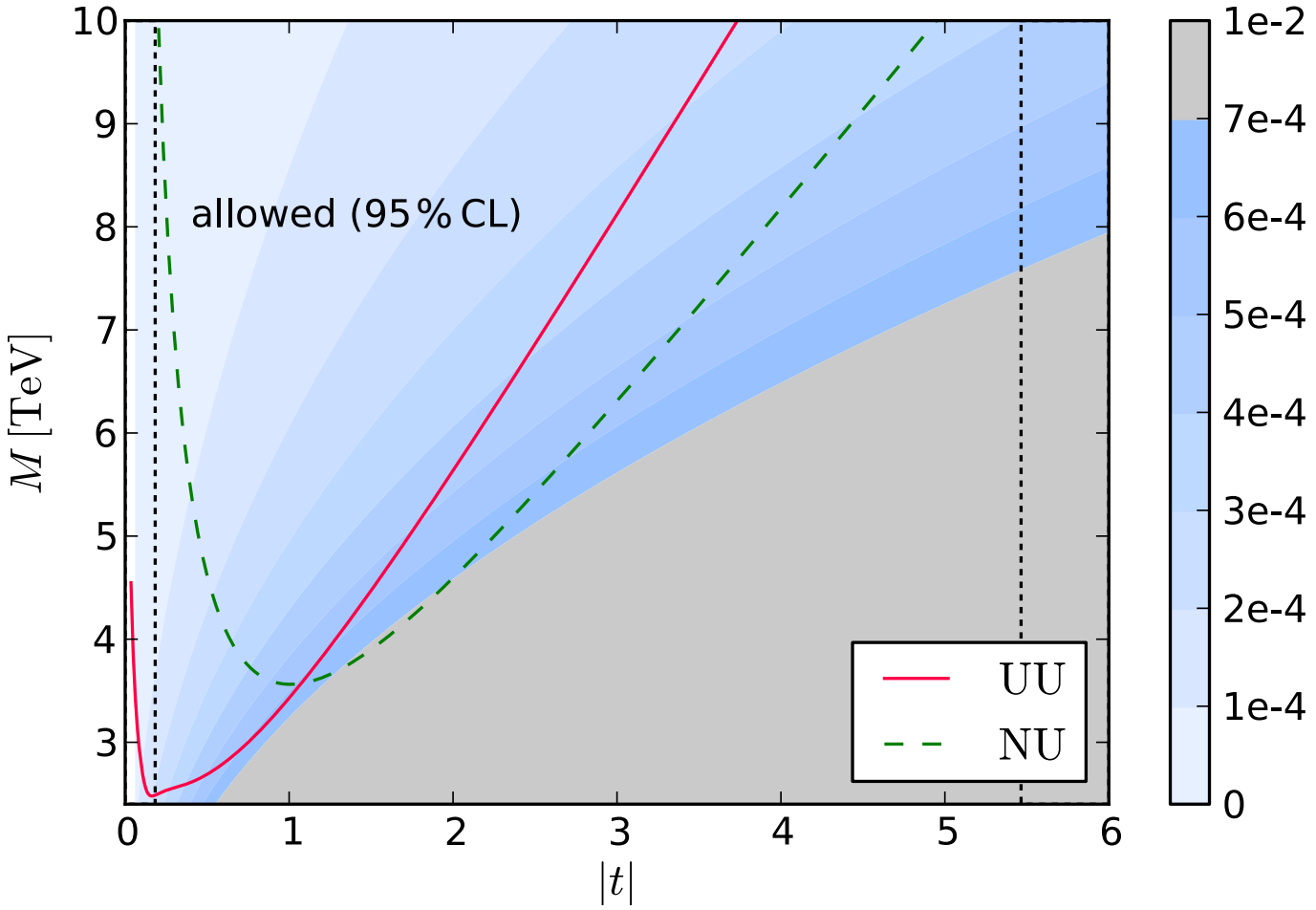
Conclusion

- Comparison of W′, Z′ production **@LO, NLO, NNLO, NLO+NLL**
- Our implementation, RESUMMINO NLO+NLL is available

- Recast the latest CMS, ATLAS analysis and extracted new limits in the SSM and $\mathcal{G}_{221}$ models
- Interferences can be very large in some models and impact strongly the exclusion limits
- Approaching the threshold region with higher masses
  $\Rightarrow$ Resummation needed


allowed (95 % CL)
UU
NU
M [TeV]
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9
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1e-2
7e-4
6e-4
5e-4
4e-4
3e-4
2e-4
1e-4
0

Model	RESUMMINO LO	PYTHIA LO	RESUMMINO NLO	FEWZ NLO	RESUMMINO NLO+NLL	FEWZ NNLO
B_1	$1338.6^{-155.5}_{+186.7}$	$1333.0^{+188.9}_{-155.4}$	$1469.2^{+119.7}_{-134.7}$	$1492.9^{+74.7}_{-79.4}\pm^{+127.9}_{-89.2}$	$1411.2^{-88.7}_{-37.2}$	$1509.1^{+25.7}_{-34.5}\pm^{+146.9}_{-92.3}$
B_2	$799.2^{+92.5}_{-111.4}$	$799.6^{+112.2}_{-91.6}$	$874.6^{+73.8}_{-83.9}$	$893.5^{+44.7}_{-47.3}\pm^{+74.9}_{-52.0}$	$843.3^{-47.5}_{-26.0}$	$902.7^{+12.7}_{-18.4}\pm^{+86.5}_{-54.3}$
B_3	$1515.4^{+175.3}_{-213.6}$	$1520.0^{+214.9}_{-176.4}$	$1672.7^{+138.9}_{-156.2}$	$1689.2^{+85.5}_{-90.3}\pm^{+145.2}_{-101.4}$	$1605.7^{-99.7}_{-44.2}$	$1705.1^{+24.2}_{-35.3}\pm^{+168.1}_{-105.7}$
B_4	$3630.9^{+420.3}_{-506.5}$	$3636.9^{+504.5}_{-427.1}$	$3986.9^{+339.9}_{-375.4}$	$4053.5^{+203.3}_{-215.3}\pm^{+341.0}_{-236.9}$	$3841.5^{-214.4}_{-112.1}$	$4094.5^{+57.6}_{-83.7}\pm^{+394.3}_{-247.6}$
B_5	$351.2^{+41.1}_{-49.0}$	$349.6^{+48.9}_{-40.6}$	$385.2^{+31.3}_{-35.7}$	$388.9^{+19.6}_{-20.8}\pm^{+47.8}_{-33.4}$	$369.9^{-23.4}_{-10.2}$	$392.6^{+5.5}_{-8.1}\pm^{+38.5}_{-24.2}$

Table: Total cross section predictions for positively charged W' bosons decaying into a positron and a neutrino at LHC14 (in attobarns) for the benchmark points defined. Interference terms between W and W' gauge bosons and the pure SM contribution are neglected. The invariant mass of the lepton pair is restricted to $Q > 3M_{W'}/4$.

Model	PYTHIA w/o int.	PYTHIA w/ int.	RESUMMINO LO	RESUMMINO NLO	RESUMMINO NLO+NLL
B_1	$1333.0^{+188.9}_{-155.4}$	$1237.7^{+175.4}_{-145.5}$	$1241.7^{+147.6}_{-176.1}$	$1379.5^{+113.4}_{-121.1}$	$1313.3^{-92.3}_{-27.9}$
B_2	$799.6^{+112.2}_{-91.6}$	$953.2^{+128.1}_{-108.6}$	$949.0^{+107.6}_{-129.5}$	$1013.8^{+90.3}_{-105.7}$	$993.1^{-37.7}_{-40.0}$
B_3	$1520.0^{+214.9}_{-176.4}$	$1684.3^{+234.3}_{-194.4}$	$1676.9^{+193.5}_{-233.0}$	$1831.2^{+158.9}_{-177.3}$	$1775.6^{-86.7}_{-57.2}$
B_4	$3636.9^{+504.5}_{-427.1}$	$3418.0^{+478.2}_{-404.0}$	$3419.4^{+398.8}_{-481.6}$	$3781.1^{+318.5}_{-343.2}$	$3618.7^{-228.5}_{-90.3}$
B_5	$349.6^{+48.9}_{-40.6}$	$317.9^{+45.3}_{-37.8}$	$317.9^{+37.6}_{-45.8}$	$351.9^{+29.5}_{-32.9}$	$332.7^{-25.4}_{-9.0}$

Table: Same as above, but with interference terms now included.

Model	New gauge boson	Previous mass limit [TeV]	New mass limit [TeV]
SSM	W'	3.27–3.28	3.5
SSM	Z'	2.90–2.96	3.2
UU	W'	2.48	3.9–4.0
UU	Z'	2.48	2.8–3.2
NU	W'	3.56	(3.5)
NU	Z'	3.56	(3.3)

Table: Previously obtained exclusion limits, using ATLAS and CMS data for the SSM as well as low-energy and precision data for the UU and NU models, and new exclusion limits, including all interference effects and NLO+NLL corrections, for W' and Z' gauge bosons.

BP – I $\mathrm{SU}(2)_1 \times \mathrm{SU}(2)_2 \times \mathrm{U}(1)_\mathrm{X}$ BP – II

$\mathrm{SU}(2)_1 \equiv \mathrm{SU}(2)_\mathrm{L}$ **Identification** $\mathrm{U}(1)_\mathrm{X} \equiv \mathrm{U}(1)_\mathrm{Y}$

Doublet $\phi \sim (\mathbf{1}, \mathbf{2}, \frac{\mathbf{1}}{\mathbf{2}})$

Triplet $\phi \sim (\mathbf{1}, \mathbf{3}, \mathbf{1})$

Bi-doublet $\phi \sim (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{0})$

$\mathrm{SU}(2)_2 \times \mathrm{U}(1)_\mathrm{X}$

$\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ u_\mathrm{D} \end{pmatrix}$ $\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 0 \\ u_\mathrm{T} & 0 \end{pmatrix}$ First Stage

$\mathrm{SU}(2)_1 \times \mathrm{SU}(2)_2$

$\langle\phi\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} u & 0 \\ 0 & u \end{pmatrix}$

$\mathrm{U}(1)_\mathrm{Y}$

$\mathrm{SU}(2)_\mathrm{L}$

$\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$ Second Stage $\mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_\mathrm{Y}$

$H \sim (\mathbf{2}, \bar{\mathbf{2}}, \mathbf{0})$ $\langle H\rangle = \frac{v}{\sqrt{2}}\begin{pmatrix} c_\beta & 0 \\ 0 & s_\beta \end{pmatrix}$

$H \sim (\mathbf{1}, \mathbf{2}, \frac{\mathbf{1}}{\mathbf{2}})$ $\langle H\rangle = \frac{v}{\sqrt{2}}\begin{pmatrix} 0 \\ 1 \end{pmatrix}$

LR-D, LP-D, FP-D, HP-D

LR-T, LP-T, FP-T, HP-T

$\mathrm{U}(1)_\mathrm{e.m.}$

UU, NU

BP	Model	$SU(2)_1$	$SU(2)_2$	$U(1)_X$
BP-I	Left-right (LR)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}, \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	$\frac{1}{6}$ for quarks, $-\frac{1}{2}$ for leptons.
	Lepto-phobic (LP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}$	$\frac{1}{6}$ for quarks, Y_{SM} for leptons.
	Hadro-phobic (HP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	Y_{SM} for quarks, $-\frac{1}{2}$ for leptons.
	Fermio-phobic (FP)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$		$Y_{\text{SM}}$for quarks, Y_{SM} for leptons.
BP-II	Un-unified (UU)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	Y_{SM} for quarks. Y_{SM} for leptons.
	Non-universal (NU)	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{1^{\text{st}},2^{\text{nd}}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{1^{\text{st}},2^{\text{nd}}}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{3^{\text{rd}}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{3^{\text{rd}}}$	Y_{SM} for quarks. Y_{SM} for leptons.